Addendum to IS449

Measurement of the isotope shift of ^{7,9,10,11}Be at COLLAPS

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Abstract

We propose to perform isotope shift measurements of Be^+ ions at the COLLAPS collinear laser spectroscopy setup. These measurements will provide a first determination of the charge radii of the beryllium isotopes ^{7,9,10,11}Be. Recent calculations of the atomic structure of Be^+ showed that the accuracy that can be expected for the collinear measurements will be sufficient to extract reasonable charge radii. The measurement will be carried out with the laser system that has been prepared for IS449. The experiment will also provide a precise determination of the acceleration voltage of the ions. Therefore we ask for test beam time at the COLLAPS beamline with stable beam from RILIS, preferably at the end of the ongoing shutdown period, and some radioactive beam in May/June 2008.

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1. Physics Motivation

A measurement of the isotope shift of ^{11}Be will provide for the first time a nuclear-model independent value for the nuclear charge radius of a one-neutron halo nucleus. To extract the nuclear charge radius information, precise calculations of the mass-dependent isotope shift are absolutely necessary for isotopes of the lightest elements [1, 2]. These calculations must reach a relative accuracy of better than 10^{-5} of the total isotope shift and are so far only possible for one-, two-, and three-electron systems [3-7]. The electron correlations are difficult to evaluate and the complicate correlation integrals can only be solved for these simple systems [8]. Another challenge lies on the experimental side: a similar accuracy must be reached in the isotope shift measurement and – at the same time – the method has to provide sufficient efficiency for the detection of exotic nuclei that are produced only in tiny amounts and have very short half-lives. This approach has so far only been successfully demonstrated on helium [9] and lithium [10-12]. In both cases spectroscopy on neutral atoms was performed: the charge radius of ^{6}He and ^{8}He was determined with spectroscopy on laser-cooled atoms in a magneto-optical trap (MOT), whereas for lithium resonance ionization mass spectroscopy was used and the produced ions were individually detected after mass separation.
We are now preparing a measurement of the charge radius of ^{7,9,10,11}Be by laser spectroscopy of single laser-cooled ions in an rf-quadrupole trap [13]. This experiment has been approved by the INTC to be performed at ISOLDE (IS449). We pursue the development of the method based on cold trapped Be^+ ions for ultimate sensitivity and accuracy.
We found recently that an alternative approach can provide meaningful nuclear charge radii of beryllium isotopes to test and to challenge nuclear theories. It is based on collinear laser

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spectroscopy with – for the first time – a frequency comb as a frequency reference. The required technical development aims to enhance the spectroscopic accuracy from which not only the present experiment but also all further collinear laser spectroscopy may profit, especially isotope shift measurements of lighter nuclei. In the following section, we discuss the possibilities of such an experiment at ISOLDE.
In parallel we would like to perform a test of accurate voltage measurements with a voltage divider that has been developed by the group of Christian Weinheimer in Münster for the KATRIN experiment in close collaboration with the PTB. It has been designed to provide an accuracy of 10^{-6}, which is more than sufficient to drastically reduce systematic uncertainties in collinear spectroscopy arising from insufficient knowledge of the acceleration voltage and, thus, the uncertainty in the ion velocity β. A simultaneous measurement of voltages and resonance frequencies in collinear and anti-collinear directions is an important test and will lead to a better understanding of these limiting uncertainties.

2. Collinear laser spectroscopy

Isotope shift measurements in collinear laser spectroscopy are based on the fact that the velocity distribution of ions accelerated in an electrostatic field is compressed [14]. This leads to a velocity spread that can be evaluated from

$$\delta E = mc^2\, \beta\, \delta\beta.$$

Since δE is constant, an increase in velocity $\upsilon = \beta c$ must result in a reduction of the velocity spread $\delta\beta$. Therefore, acceleration to about 60 keV gives a residual Doppler width of the fast ensemble in the order of the natural lineshape of typical dipole transitions. This method has now been used over decades by the COLLAPS collaboration to determine nuclear charge radii and electromagnetic moments of short-lived nuclei. Ions or atoms in fast beams are excited by laser radiation in collinear or anti-collinear geometry and the excitation is detected by various means of detection: resonance fluorescence, resonance ionization and ion detection, collisional ionization or even ß-asymmetry. Typically, measurements are performed by keeping the laser frequency constant and recording the resonance signal as a function of the variable voltage applied to the charge-exchange cell (atoms) or the detection region (ions) that determines the atom/ion velocity. Due to the Doppler Effect, the laser frequency in the ions rest frame is changing according to

$$\delta\nu = \nu_0\, e / (2eU\, mc^2)^{1/2}\, \delta U,$$

which, in the case of beryllium, gives a Doppler-tuning coefficient of approximately 30 MHz/V. Due to this large coefficient, the isotope shift measurement is also very sensitive to drifts in the total acceleration voltage. To avoid systematic effects, the standard procedure is a fast switching between different isotopes. In this case a slow drift results only in an artificial line broadening. However, the required measurement of the acceleration and post-acceleration voltages limit the final accuracy that can be achieved with this method.
We propose a procedure that will avoid this kind of uncertainty by measuring the absolute transition frequency with high precision, independent of the ion beam velocity. To do so, two lasers will be applied: one laser is used in collinear, the other one in anti-collinear geometry. Absolute frequencies of the lasers are determined by locking the two lasers to an iodine line at a known frequency and to a frequency comb, respectively. The resonance frequencies of the transition in the laboratory frame are given by

$$\nu_{\text{coll}} = \nu_0\, \gamma\, (1+\beta)$$

and

$$\nu_{\text{anti-coll}} = \nu_0\, \gamma\, (1-\beta),$$

respectively. If both frequencies are measured simultaneously, the absolute transition frequency can be calculated using

$$\nu_{\text{coll}} \times \nu_{\text{anti-coll}} = \nu_0^2 ,$$

which is completely independent of the absolute ion beam velocity β and its uncertainty.
Taking into account the experience from former beam times with beryllium ^{7,9,10,11}Be [15, 16], we expect to reach an accuracy on the order of a few MHz for the isotope shift. This will provide a first test of the recent calculations performed by Z.-C. Yan and G.W.F. Drake and nuclear charge radii can be extracted with a reasonable accuracy. The trap measurements to be performed later with BeTINa will have a considerably improved uncertainty. The beam time requested here has mainly three goals:

(I) Determination of a first value for the change of nuclear charge radius between ^{7,9,10,11}Be
(II) Experimental development to increase the precision of collinear laser spectroscopy on light nuclei at COLLAPS.
(III) Test of the setup and installation of the laser system that will also be used for the BeTINa (IS449) experiment.

Another trap experiment – similar to IS 449 - is currently being prepared at RIKEN and the group has already published first results [17]. However, their accuracy is still neither sufficient to test the atomic physics calculations nor to extract a nuclear charge radius.

3. The Setup

The resonance transition frequency of the $2s\ ^2S_{1/2} \rightarrow 2p\ ^2P_{1/2}$ transition in Be^+ is 313 nm. We have set-up two dye lasers operating at 626 nm which will both be frequency doubled to obtain a few mW of ultraviolet wavelengths. The light will be used for collinear spectroscopy in collinear and anti-collinear geometry at the COLLAPS setup as shown in Fig. 1. The resonance signal will be detected by fluorescence detection with ultraviolet-sensitive photomultipliers.
The resonance signal will be obtained in the following way:
One of the two dye lasers will be locked to a hyperfine transition of the iodine molecule. It

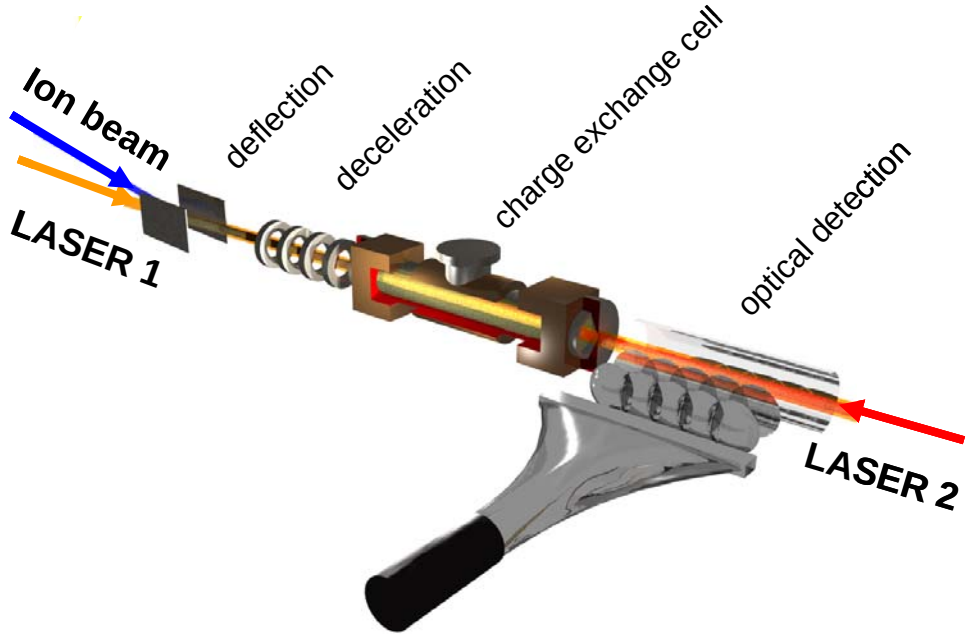

Figure 1: The COLLAPS setup with charge exchange cell (which is not operated for the beryllium spectroscopy) and the optical detection region. Fluorescence from the counter- and the co-propagating laser beam is detected.

will be kept fixed in frequency during the complete beamtime. A number of iodine lines are available in the region where resonance fluorescence will be expected with the frequency-doubled light and Be+ ions accelerated to energies between 40 and 50 keV. For instance, the a_1 hyperfine component of the $X\ ^1\Sigma^+_{0g} \rightarrow B\ ^3\Pi^+_{0u}$ R(48) 8-3 fine structure transition appears at 16018.30403 cm^{-1} [18]. If the laser is locked to this transition, the $^9Be^+$ ions have to be accelerated to 47.743 keV to be in resonance with the laser beam in collinear geometry.
The second laser will be locked to a frequency comb. This gives us the possibility to tune the laser precisely and accurately to any arbitrary frequency in the interesting range. It can also be continuously scanned by changing the repetition rate of the comb. If this laser is now tuned to 15910.6216 cm^{-1} and superimposed with the ion beam in anti-collinear geometry, it is also in resonance with the Be+ ions. Doppler tuning and fast beam switching with acousto-optic modulators will be used to record the resonance profiles in both geometries simultaneously. From the resonance curves and the fit-results we can then determine the rest-frame frequency of the transition. This will be repeated for each hyperfine line.
The measurement will benefit from recent calculations of the isotope shift in this transition by Gordon Drake and Zong-Chao Yan. From these we know the resonance positions very accurately, only the field shift on the order of a few MHz is not known. In our lithium measurements we found that the resonances were exactly where they were predicted. Therefore we do not need much time to search for the resonance.
The simultaneous measurement in collinear and anti-collinear geometry provides a determination of the rest frame transition frequency of all studies beryllium isotopes with a drastically improved accuracy. If this value is being compared with the collinear or anti-collinear resonance frequency, the velocity of the ions and therefore the exact acceleration voltage can be calculated precisely [19].

Additionally we plan to measure the acceleration voltage of the ions during the run with a high-voltage divider to a precision of better than 10 ppm. Such a divider has been developed in the group of Christian Weinheimer from the University of Münster in collaboration with the German PTB in Braunschweig. To do so, the voltage at the ISOLDE ion source will be measured before and after the run with this device. During the run, it will be connected to the COLLAPS high-voltage supply for the detection region which is used to perform Doppler tuning. This test has several goals:
(a) to deliver accurate voltage information during the run to find the resonances quickly,
(b) to test the performance of such high-precision voltage measurements for routine operation of collinear spectroscopy and to determine how well the applied voltage agrees with the final acceleration voltage of the ions[†],
(c) if successful, similar measurements could be performed in the future with the ISCOOL cooler and buncher. It will help to provide precise voltage information there and the exact potential of the accumulated bunch in the cooler.

The laser installation at CERN as well as the locking scheme of the lasers and the detection of the UV light will also serve as a preparation and test for the beryllium trap-spectroscopy with the linear Paul trap at the end of the ISOLTRAP beamline.

[†] Leakage currents, plasma and contact potentials will have an influence on the potential difference experienced by the ions.

4. Status of Preparation and Required Beam Time

The laser setup has been developed in Mainz. Both dye lasers are in operation, one dye laser has been locked to an iodine line, the iodine FM saturation spectroscopy is almost finished. The laser stabilization to the frequency comb was realized in a diploma work and the precise frequency scanning was demonstrated in the spectroscopy of lithium isotopes.
An improved design of apertures that will be included into the COLLAPS beamline to suppress laser straylight has been designed and is being machined in the workshop in Mainz. The frequency doublers are available and have been tested. Final optimization is going on.
The voltage divider is being built in Münster. It might be ready early in May but is not absolutely required for the test measurements. It is most important to have the divider during the online run, which we would like to perform in summer.

For testing this approach to precision spectroscopy on light nuclei we request a beam of stable beryllium ions produced by the laser ion source RILIS. **8 off-line shifts** should be sufficient for careful optimization and test of the setup. If possible this should be foreseen for the end of the shutdown period in April. For the **on-line** run we apply for another **12 shifts**. If possible the on-line run should be scheduled shortly after the off-line optimization, to avoid the necessity to remove and reinstall the laser system. However, a period of 3-4 weeks should be left between the off-line and on-line run to allow for necessary changes and improvements.

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